Development of Miniaturized Intra-Cavity DFG, Fiber-Optic, and Quantum Cascade Laser Systems in Conjunction with Integrated Electronics for Global Studies of Climate Forcing and Response using UASs as a Partner with Satellite and Adaptive Models.

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Abstract- **In order to harness the power of UASs for *in situ* atmospheric monitoring of tracers such as CO_2, N_2O, and CH_4 and as a precursor for extending detection limits to encompass sub-ppb level species, we have developed small, lightweight, single mode laser systems with co-developed integrated electronics. The laser sources are of various types including newly developed pump-enhanced difference frequency generation (PE DFG), distributed feedback quantum cascade lasers (DFB QCLs), and new types of commercially available DFB diode lasers. All are continuous wave (cw) and thermo-electrically cooled, ensuring a high instrument duty cycle in a compact, low maintenance package. The light sources are collimated with miniature aspherical lenses and coupled into a home-built astigmatic Herriott cell for detection of the various targets using direct absorption. In parallel with the optical components, we have developed integrated electrical systems for laser control, data processing, and acquisition. A prototype instrument suite is described that illustrates the importance of co-development of optical and electrical components in achieving an apparatus that is compact, fully automated, and highly capable scientifically. Although the emphasis here is on atmospheric tracers, we are already applying these technologies to spectroscopic measurements of other atmospheric species such as isotopes, free radicals, and reactive intermediates in order address several urgent science priorities defined by the NRC.**

I. INTRODUCTION

The 2007 National Research Council (NRC) report, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, delineates and array of challenges facing society as the global climate system passes through a period of unprecedented changes. The Decadal Survey goes further, recommending specific science missions that will concentrate NASA's tremendous technical resources on meeting these challenges. Central to completing these science missions will be the effective union of breakthrough electro-optical technologies with emerging Uninhabited Aerial Systems (UAS), allowing for satellite validation and independent science missions of unprecedented duration and scientific capability, in effect linking NASA's orbital and sub-orbital programs to each other and to the objectives of society as a whole.

Here we describe an array of flight-hardened miniaturized technologies for next generation tunable diode laser spectrometers along with a brief description of two new flight instruments that will demonstrate the successful integration of the electro-optical, data acquisition, signal processing, and computing technologies.

II. LASERS AND OPTICS

A. *Difference Frequency Generation*

Recent advances in both infrared laser sources and optical detection methods promise to allow unprecedented accuracy and precision in the study of trace atmospheric species. For example, Integrated Cavity Output Spectroscopy (ICOS),[1] developed within NASA's IIP program, has demonstrated remarkable sensitivity using cryogenically cooled quantum cascade lasers (QCLs) at 6.7 μm. In particular, using off-axis alignment geometry, a noise equivalent absorption sensitivity of 1.2×10^{-12} cm^{-1} was demonstrated for a 110 cm optical path in one second. Additionally, the apparatus was found to be robust and environmentally stable over extended periods of time. However, extending this method into the parts of the mid-IR where QCLs are not an option requires the use of a different laser source.

To interface properly with ICOS, a laser source must possess several qualities, including high power (> 5 mW), low noise, rapid tunability, excellent spatial quality, and robust, single-frequency operation. The successful extension of off-axis ICOS into the 3–5 μm region would allow several important species to be studied with unprecedented detail using essentially a single apparatus, including formaldehyde, acetylene, ethane, ethylene, HCl, HCN, CO, N_2O, and CH_4. Although traditional single-pass difference frequency generation (DFG)[2] using COTS telecom lasers can be used to produce tunable single mode light between 3 –5 μm, the efficiency of these systems is rather poor, such that the amount of mid-IR power (< 1 mW) is generally too low to be used effectively with off-axis ICOS.

We have therefore devised and tested a different approach called pump-enhanced difference frequency generation (PE-DFG). Pump enhancement has been applied quite successfully in SRO systems for many years in order to decrease the oscillation threshold of these devices. However, as both the pump and signal frequencies are resonant with the optical cavity, tuning the laser requires actively scanning the cavity length. With PE-DFG, rather than allowing the signal beam to spontaneously generate within the cavity, we supply it using a separate laser which is not amplified by the ring cavity, allowing for the signal (and idler) frequency to be tuned at will by current tuning over the range of the DFB signal laser.

The pump laser used (1064 nm) consists of a FBG stabilized diode laser (Innovative Photonics Solutions) with two stages of built in isolation mated to a polarization maintaining Yb-doped fiber amplifier (NovaWave Technologies) for a total power of 800 mW and a linewidth <10 MHz. The signal laser (1500 – 1600 nm) is constructed by mating a commercial telecom DFB diode (Lucent) to a polarization maintaining 1 W Er-doped fiber amplifier (IPG Photonics). The pump and signal lasers are combined in a NovaWave polarization maintaining micro-optical wavelength division multiplexer (PM-WDM), ensuring that pump and signal lasers are co-aligned and polarized in the same direction. The output of this fiber is focused into the PPLN cavity using a single achromatic lens. The distance between lens and fiber can be adjusted over a small range using an Oz Optics adjustable fiber connector in order to achieve optimum mode-match between laser and cavity. The ring cavity is a home-built assembly that contains four kinematically adjustable mirrors with unique coatings for optimum reflection of 1064 through the cavity and high transmission of 3.3 μm thorough mirror 4. Mirror 2 is mounted on a piezoelectric actuator (PZT, Physik Instrumente P-888.30) so that applying 0-100 V changes the total cavity length by several free spectral ranges (FSR). Table 1 gives the radii of curvature and measured reflectivities (both sides) of the cavity mirrors. The PPLN crystal (Stratophase, PPLN OPO3) is 40 mm long and 0.5 mm thick and includes 9 poling periods from 29.50 – 31.75 μm for optimum QPM at a variety of signal wavelengths over the range 1500-1600 nm. The PPLN crystal is mounted on a single stage thermoelectric cooling/heating element, allowing its temperature to tuned from 0 – 70 ºC and it is AR coated at the pump, signal, and idler wavelengths. The PPLN oven is translatable within the cavity to allow access to the various poling periods with only minor realignment. The adjustable focuser is used to produce a 300 μm beam waist between mirrors one and two in order to achieve the optimum 60 μm waist in the PPLN crystal needed to match the confocal parameters of the cavity to that of the crystal. A photograph of the pump enhancement cavity is shown in Figure 1 along with the pump beam cross sections observed during alignment.

The pump laser is locked to the enhancement cavity containing using the Pound-Drever-Hall (PDH) technique, while the signal laser is single-passed. Tuning the signal laser allows the mid-IR idler beam to be tuned while the pump laser frequency remains fixed. Currently, using 800 mW of 1064 and 1200 mW of 1543 nm, we produce 5 mW of single mode, tunable light at 3.43 μm.

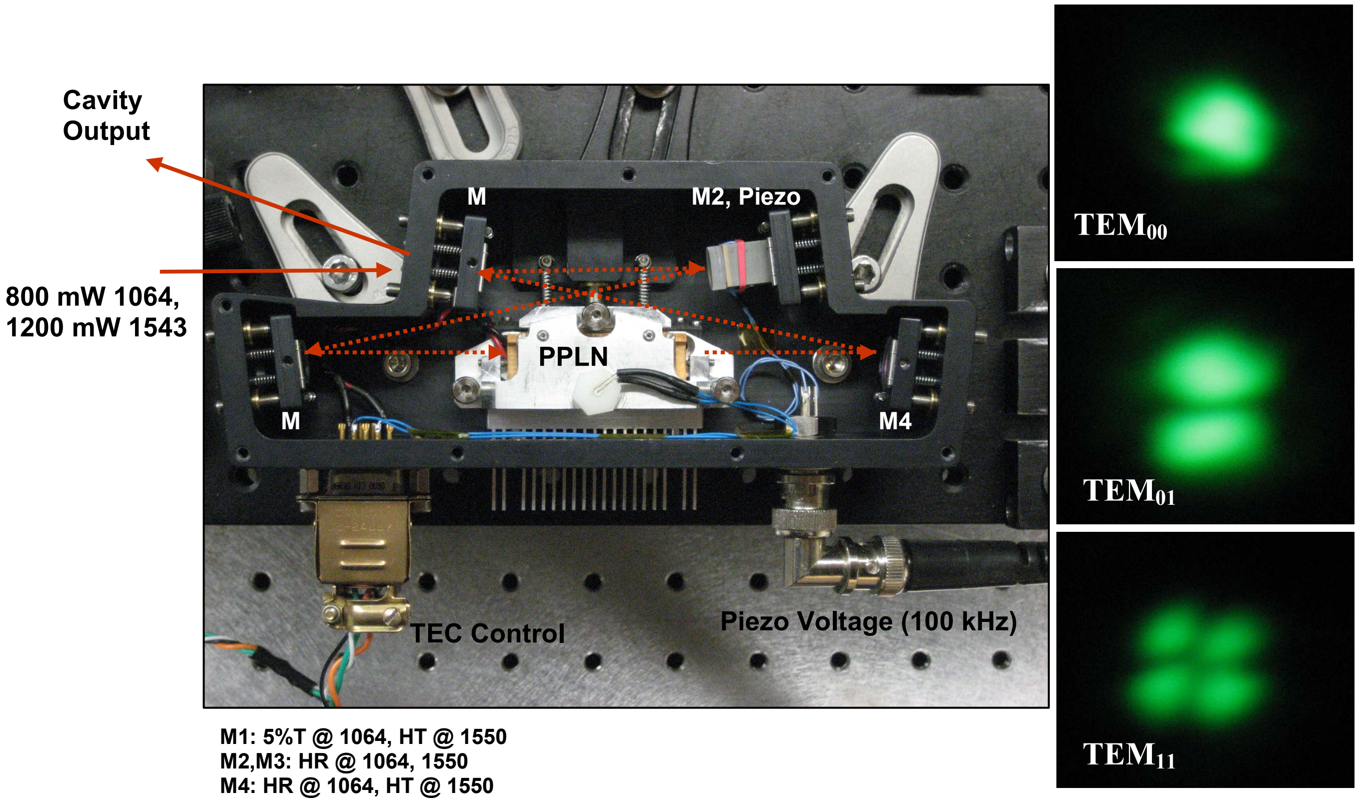

Fig. 1. A singly resonant, pump enhanced, difference frequency generation cavity is shown to the left. Two near-IR lasers are combined in a periodically poled lithium niobate (PPLN) crystal to generate coherent mid-IR light. The cavity is resonant with the 1064 nm near-IR source, allowing for a resonant buildup of power for this pump laser. At right are photos showing the transverse modes supported by the cavity. Cavity mirrors are adjusted until only TEM_{00} is supported.

B. Quantum Cascade Laser (QCL)

Quantum cascade lasers (QCLs) are unipolar semiconductor lasers based on so-called intersubband transitions, i.e. radiative transitions which take place between confined electronic states of the conduction band of multiple quantum-well (QW) heterostructures.[3] A key feature of QCLs is that the emission wavelength is primarily a function of the QW thickness. As a consequence, QCLs can cover a wide spectral range using the same material system. So far, the devices showing the best performance in the wavelength range of interest for the present project ($\lambda \sim 6 - 10$ µm) are based on InGaAs/InAlAs alloys lattice-matched to InP, which is a material system widely used in optoelectronics.

At the cutting edge of today's QCL technology are devices that can operate in continuous wave (cw) mode at temperatures accessible by multistage thermoelectric coolers (T > 230K).

We have developed an innovative opto-electronic package for housing an 8 µm cw QCL, shown in Fig. 2. This fan-cooled housing has a built-in 2 stage TE cooler for cooling cw lasers to –25 ºC, and incorporates 5 mm focal length AR coated aspheric lens whose distance from the laser chip can be adjusted over a range of 2 mm to optimize the mode match between laser and cavity. A wedged exit window prevents destabilizing feedback from coupling into the laser. Replacing the traditional cryogenic QCL with this TE cooled assembly not only results in dramatic savings in instrument weight and volume, but will allow the laser to be operated unattended for days and perhaps weeks on end—both advantages will be critical to the effective use of UAS based tunable infrared laser spectroscopy. This laser will form the optical centerpiece of the TILDE flight instrument described in section IV.

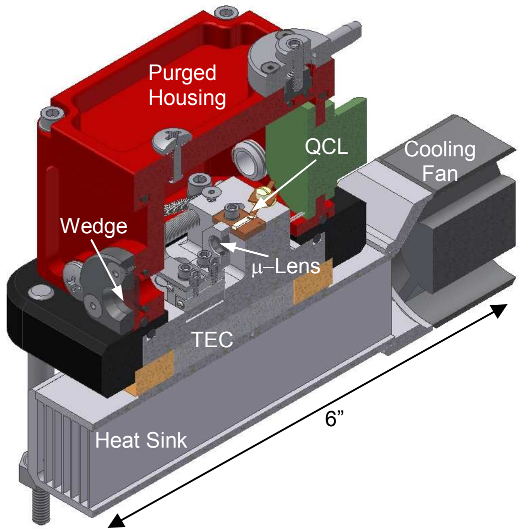

Fig. 2. Newly Developed QCL Housing For TE Cooled QCL Devices. Built-in collimation is accomplished with miniature aspheric lens. Temperature is recorded on both sides of the TEC and in the N_2 environment inside the housing.

III. FLIGHT ELECTRONICS

In order to merge this new class of high power, highly collimated lasers with the Earth science objectives set forth by the NRC, carefully designed miniaturized electronics systems must be integrated in all phases of the spectroscopic measurement chain, including the QCL TEC controller, programmable injection current source, return signal anti-aliasing filter and preamplifier, analog to digital converter, signal processing engine, and on-board data storage

From a signal-to-noise point of view, the most demanding of the electrical subsystems are the laser current driver and the data acquisition system. Beginning with the laser current supply, we have designed, fabricated and flight-tested a new Quantum Cascade Laser Current (QCLI) board capable of providing up to 1 A of QCL current with 50 μA RMS of current noise. An arbitrary waveform with a selected duty cycle is programmed into the on-board memory and delivered to the laser using either an internal trigger from the built-in timing function or an external trigger from the A/D board, allowing for precise synchronization between the two. The QCLI has been repeatedly flight-tested in the stratosphere aboard NASA's WB-57 and has achieved its laboratory noise and jitter specifications each time. The QCLI is pictured in Fig. 3.

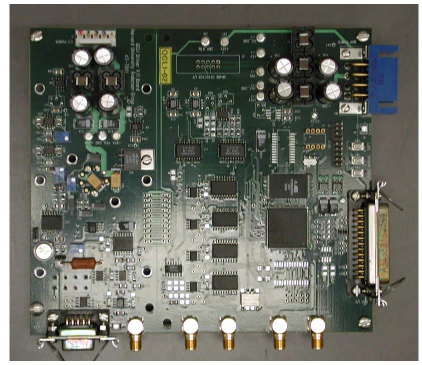

Fig. 3. Quantum Cascade Laser Current Driver (QCLI)

Previously, onboard computer processing capabilities have dominated the weight and size of many flight instruments designed for airborne platforms. Leveraging advances in PXI hardened computer platforms, PC board fabrication, surface mount electrical components, field programmable gate arrays (FPGA), we have developed a scalable data acquisition architecture that allows digital conversion and distributed processing at the detection axis with Ethernet communications to the main computer. This so-called Scalable Signal Processing (SSP) board couples a 16-bit analog to digital converter along with an FPGA based signal processing engine, allowing for digitized spectra to be averaged and reduced before storage on the computer. This reduces the requirements on the main computer, thereby reducing its size and weight while increasing the number of possible recorded channels. The SSP board is pictured in Fig. 4.

Figure 5 shows the opto-mechanical layout of the HHH instrument.

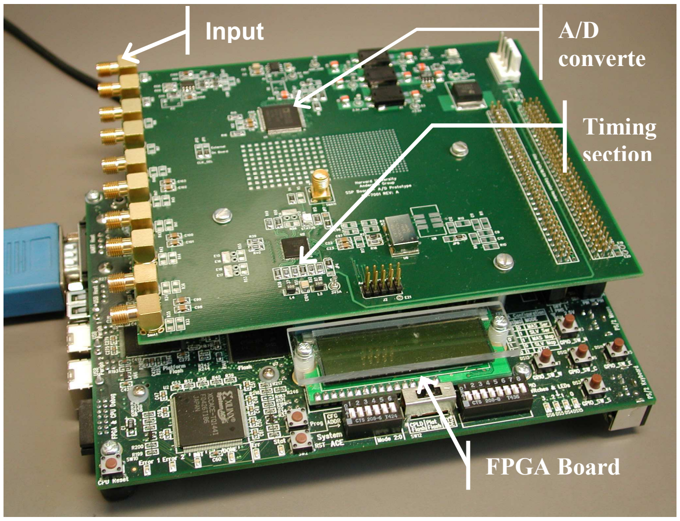

Fig. 4. SSP data acquisition board prototype. Top board is responsible for A/D conversion, power distribution, and timing control. Bottom board is Xilinx FPGA evaluation board used for signal processing and Ethernet data transfer.

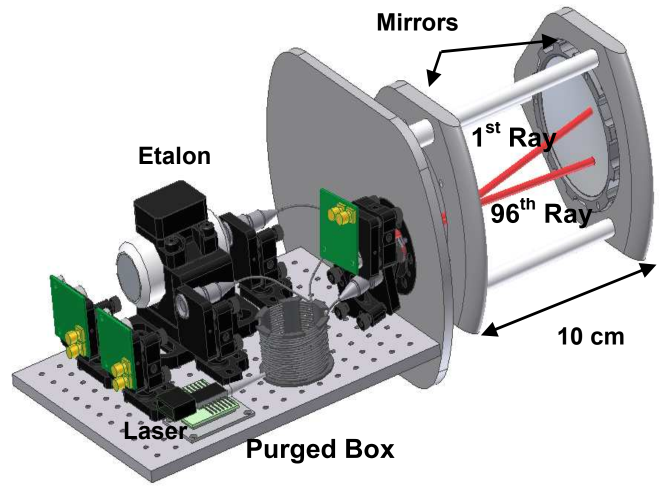

Fig. 5. CAD model of Harvard Herriott Hygrometer in flight configuration. The instrument utilizes a fiber coupled DFB laser, which allows it to be split into three beams using a custom fused beam splitter. About 90% of laser light is coupled into the 10 m absorption cell and the two other channels are used for wavelength reference (Etalon) and background water subtraction.

IV. INTEGRATED FLIGHT INSTRUMENTS

A. Harvard Herriott Hygrometer (HHH)

Because of its high tropospheric mixing ratio and large infrared absorption cross-section, water vapor is considered the most important greenhouse gas. The vertical and latitudinal distribution of water vapor, as well as its phase allocation, therefore play a major role in setting the radiative balance of the atmosphere. In addition to its climate forcing implications, however, stratospheric water vapor also regulates ozone in the stratosphere and is therefore coupled to human health in a very direct way.

Despite the obvious need for an accurate, highly resolved set of water vapor measurement time series, strong disagreement of water vapor mixing ratios observed in the upper atmosphere exist between the satellite instruments and the *in situ* ones. The HHH instrument is designed to help resolve this glaring disparity by establishing a “gold standard” *in situ* measurement, whose mixing ratio determinations in lab and in flight are tied to SI traceable standards.

B. Tunable Infrared Laser Diode Experiement (TILDE)

Certain small molecules with fairly long atmospheric lifetimes (days-months) can be used to trace the movement of an air parcel through the atmosphere. Parcels originating from a certain event will have characteristic concentrations of each species, and characteristic ratios between them. This information is of critical importance for chemical and transport models of the atmosphere. Using the technology developed during this program, we have built an instrument for the simultaneous *in situ* measurement of several CO_2, N_2O, and CH_4. A schematic of the TILDE instrument is shown in Fig. 6.

In addition to incorporating the breakthrough technologies discussed above, TILDE has a number of other innovative features that allow for high precision and accuracy in an ultra-compact package.

For one, the custom-made 36 m astigmatic Herriott cell is oriented normal to the optical table. The instrument then has an overall cylindrical symmetry that allows for facile coupling of multiple laser beams into the cell at one time. We achieve additional compactness by using custom diamond turned achromatic lenses for laser collimation as opposed to off-axis-parabolic mirrors and by using special dichroic beam splitters to propogate a fraction of each beam through a single Germanium etalon. These etalon signals provide an essential diagnostic for evaluating laser performance and drift in flight and have proven at least as valuable as reference cells for achieving the highest precision possible.

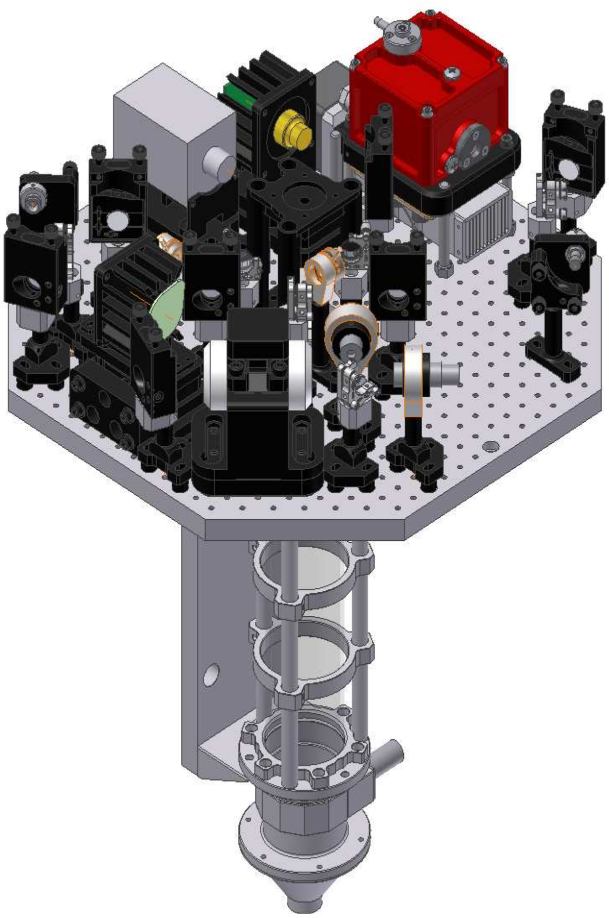

Fig. 6. The TILDE instrument uses only thermoelectric cooling for lasers and detectors allowing which is not only beneficial in the size and weight savings, but will also allow TILDE to operate unattended for hundreds of hours at a time.

The TILDE and HHH instruments will be test flown aboard the NASA WB-57 in August 2008. Once the laser and electronics technologies discussed above have been flight proven, we will prepare TILDE and HHH for subsequent deployment aboard a UAS.

Importantly, advancement of the electro optical subsystems will benefit other infrared applications as well, such as Light Detection and Ranging (LIDAR), which will be central to a number missions prescribed by the NRC. For instance, the QCL housing and collimation system described below could well become the precursor to an airborne mid-IR LIDAR system, either for chemical sensing or cloud profiling purposes. Additionally, the miniaturized, high speed, 16 bit analog to digital converter with built in programmable signal processing capability (SSP) could constitute a substantial savings in size and weight on the receiving end of a LIDAR instrument. In flight qualifying the miniaturized electro-optic systems developed during this program, we have therefore not only advanced technology needed to examine water vapor and atmospheric tracers, but have advanced the technological framework that underpins virtually every laser based instrument

Looking ahead, we are working to harness this technology for the measurement of carbon isotopes in the arctic. While the entire human enterprise contributes just 8 gigatons of atmospheric carbon per year (GtC/year), the arctic permafrost reservoir represents at least 600 GtC and the immense oceanic reservoir could be larger than 11,000 Gt/C. Clearly, if even a small fraction of the permafrost or oceanic stock is released, the carbon cycle could be pushed irretrievably out of balance on the time scale of human history. Understanding the evolution of the Arctic's incoming and outgoing carbon dioxide and methane fluxes is therefore of overriding importance.

In order to effectively track the flow of CO_2 and CH_4 out of these delicate systems, the technology described here will be combined with the powerful Integrated Cavity Output Spectroscopy (ICOS) approach to distinguish between methane and carbon dioxide *isotopes* Figure 7 illustrates the spectroscopic novelty of the ICOS absorption approach, where the removal of the mirror coupling hole and the highly reflective mid-IR coatings allow

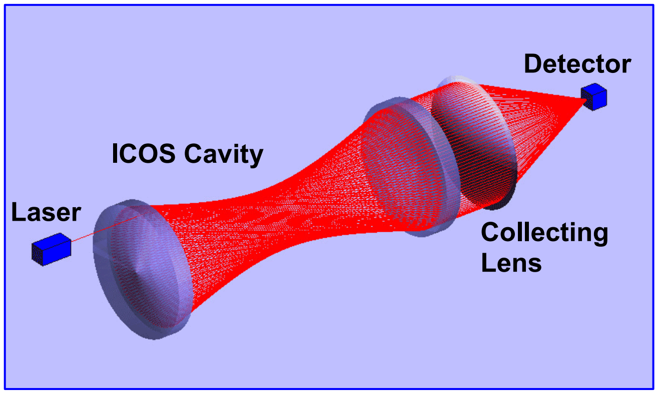

Fig. 7. Ray trace simulation of ICOS showing how highly reflective mirrors are used to trap light for thousands of passes.

for pathlengths that are 10^4 times the mirror separation. We believe that the laser and electronic subsystems described here will advance the ICOS technique to the point where it can address not only the urgent high-latitude carbon cycle dynamics, but studies of virtually any trace gases with concentrations ranging from a few parts per trillion to many parts per million.

V. CONCLUSIONS

The scientific questions in atmospheric science shift much of the burden for long-term measurements to the satellite platforms and demand a fundamentally new approach to *in situ* instrumentation with an emphasis on improved spatial and temporal coverage. The next generation of *in situ* atmospheric instrumentation must therefore be compatible with UAS platforms. We have developed a portfolio of miniaturized laser and electronics technologies to adapt existing and future instrumentation for operation on a UAS.

ACKNOWLEDGMENT

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